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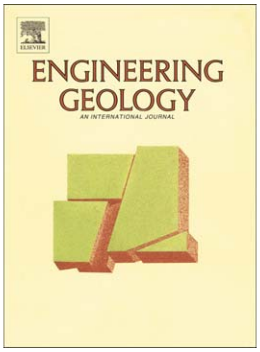

Petrographic features as an effective indicator for the variation in strength of granites

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TITLE PAGE

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Petrographic features as an effective indicator for the variation in strength of granites

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Abstract

The textural characteristics of four different granites from the lower Himalayan regime in north-western Pakistan have been examined in relation to their effect on the mechanical nature of rock. Detailed petrographic examination and subsequent quantitative QEMSCAN analysis provide better understanding of the difference between their textures. Three of the granite types are slightly altered (Grade-II) whereas the other has a higher degree of alteration and corresponds to alteration Grade-III. The mechanical properties determined for each granite type include: unconfined compressive and tensile strength, elastic modulus, P-wave velocity, Schmidt hardness and dry density. Statistical analyses, combined with post-test petrography, demonstrate textural control on mechanical properties. The important petrographic characteristics influencing mechanical behaviour include modal concentration and grain size of individual minerals, mean grain size of rock and distribution of grain size within a rock. Recrystallization of minerals along boundaries has a pronounced effect on increased strength of granites. Texture, however, has a significant influence on the variation of strength of granites with similar alteration grade.

Keywords

Petrography; Granites alteration; Mechanical properties; Recrystallization textures; Fractures propagation

1. Introduction

Evaluation of the physical and mechanical characteristics of granites is essential when considering their industrial use and/or application e.g. for use as dimension stone or building material. Alteration of granites can have a detrimental effect on engineering behaviour and significantly change the behaviour of granites in different environments/conditions e.g. exposure to moisture/temperature, mechanical load etc. A number of researchers have previously described the cataloguing of granites based on their weathering and alteration (Brown, 1981; Hencher et al., 1990; Hencher and McNicholl, 1995; Anon, 1995; Irfan; 1996; Momeni et al., 2014). Several researchers have shown an inverse relationship between the strength of granite and increasing degree of alteration. Coggan et al. (2013)

presented increasing kaolinization/alteration and associated changes in mineralogy to be responsible for a marked reduction in strength of granites from south-west England. Sousa (2013) evaluated the effect of mineral characteristics on the behaviour of different Portuguese granites including mineral weakening, quartz fissuration and type of contact between quartz with quartz and other mineral groups. He showed that evaluation of textural characteristics of quartz were vital for understanding the mechanical behaviour of granites. The influence of mineralogical composition and water content on the mechanical behaviour of argillite is described by Hu et al. (2014). The strength and elastic moduli was found to be significantly affected by increasing clay and water content. Rigopoulos et al. (2014) investigated ultrabasic and basic rocks from Greece to establish the relationship between mechanical and petrographic features. They revealed that strength tended to improve as the ratio between soft to hard minerals, ratio between secondary to primary phases and the degree of serpentinization decreased. Basu et al. (2009) assessed the engineering characteristics of altered granites from Brazil. They noticed that several alteration features, including mineralogical reform, disruption of existing textures and initiation of new cracks caused a reduction of strength of granites. The effect of weathering/ alteration on porosity and compressive strength of various rock types from Turkey was presented by Tugrul (2004). He proposed that micro-textures in relation to weathering of rocks were the controlling factors that influenced their physical and mechanical properties. Sajid and Arif (2014) investigated the effect of textural varieties on the mechanical behaviour of Utla granites from north-west Pakistan. They found that increased porosity and water absorption due to extensive recrystallization and associated mineralogical changes to be responsible for reduced strength of fine grained granites.

From the literature, researchers have observed a change in the mechanical behaviour with increased alteration grade; however, significant variation in strength is also observed in granites with similar alteration grade. The major objective of the current study is to describe the possible factors related to textural differences that are responsible for this mechanical variation in granites with analogous alteration. Pre- and post-test petrographic characteristics are compared to examine the influence of textural parameters (grain size, grain boundary recrystallization, modal concentration) on fracture propagation and engineering behaviour. Four texturally different granites types (Mansehra granite: MG, Malakand granite: SG, Utla granite: UG, Ambela granite: AG) from the lower Himalayan regime of north western Pakistan (Fig. 1) have been used to investigate this phenomena.

2. Geology of Studied granites

The Kohistan Island arc is separated from the Indian plate in north Pakistan by a regional fault known as the Main Mantle Thrust (Burg, 2011) (Fig. 1). The Khairabad fault divides the Indian plate into the northern internal metamorphosed zone and the southern external un-metamorphosed or low-grade metamorphic zone (Treloar et al., 1989) (Fig. 1). All the granitic bodies in this study (MG, SG, UG and AG) lie towards the north of the Khairabad fault, but represent different magmatic episodes. UG and MG exhibit similar mineralogical and chemical characteristics (Sajid et al. 2014) but texturally different varieties can be found in both of these plutons. MG yields whole-rock Rb–Sr age of 516 ± 16 Ma and intrudes Pre-cambrian Tanawal quartzite (Le Fort et al. 1980). AG has an alkaline signature and can be related to Permian rifting in the northern margin of the Indian plate. The detailed petrography of AG is presented in Rafiq and Jan (1988). Le Bas et al. (1987) and Khattak et al. (2008) suggested that the alkaline magmatism occured in two episodes; one in the Permian followed by another during the Paleogene (Oligocene) resulting in the formation of SG. However, Jan and Karim (1990) oppose episodic magmatism and suggest both SG and AG are the product of a single magmatic event during the Permian. The geochronological account of the alkaline rocks and other related suites are presented in more detail in Ahmed et al. (2013).

3. Methodology

Fresh bulk samples from all the four granite types were collected, processed, prepared and tested according to International Society of Rock Mechanics (2007) guidelines. All the tested samples were free of any kind of visible fracture. Strength tests were conducted using the MTS servo-controlled hydraulic testing machine at the Camborne School of Mines, University of Exeter, UK. LVDT (Linear Variable Displacement Transformer) was used to record the axial displacement. In addition, an electric resistance 2.54 mm long strain gauges were used for measurement of lateral strain. Care was taken to avoid any feldspar mega-cryst while fixing strain gauges on the samples tested. A pulse generator unit with two transducers (a transmitter and a receiver) with a frequency of 55kHz was used for determination of ultrasonic velocities of five representative samples of each type of granite tested.

A texturally representative thin section from each granite type was also processed with a QEMSCAN-4300 in the analytical facility at the Camborne School of Mines. QEMSCAN is a widely applied technique to acquire quantitative mineralogical data for analysis of mineral association, micro-textures, textural connections and quantitative mineralogy of rock specimens (Gottlieb et al., 2000). Each thin section was measured using field scan mode at a resolution of 10 microns, and data was processed as described by Rollinson et al. (2011). Petrographic studies were performed using a Nikon Eclipse E600 polarizing microscope with attached 5MP digital camera on polished thin sections obtained from each granite type. Polished thin sections were also taken from failed samples that had been subjected to strength testing to observe the propagation of newly formed fractures and their relation to grain boundaries. Failed core samples were mounted in epoxy resin for three days to preserve the new fractures and to avoid disturbance of samples during thin section preparation. The micro-petrographic index (I_p) defined as the ratio between unaltered minerals to altered minerals and fractures (Irfan, 1996; Irfan and Dearman, 1978) was also determined from twelve representative thin sections obtained from the studied samples.

4. Petrographic characteristics of studied granites

Core specimens and mineral maps (generated through field scan analyses via QEMSCAN) of the studied granites are presented in Figures 2 and 3 respectively. Petrographic characterization based on quantitative mineralogical data from QEMSCAN and microscopy was undertaken. The modal concentration of minerals and their mean grain sizes are presented in Tables 1 and 2 respectively. The detailed petrographic characteristics of each granite type are described as:

a. Utla granites (UG)

UG is a mega-crystic granite with K-feldspar and plagioclase constituting most of the phenocrysts. Plagioclase ranges in alteration from fresh to partially altered grains; however, completely altered feldspar megacrysts are also observed in some thin sections (Fig. 4A). Sericite, kaolinite and fine grained epidote are the most common alteration products observed. Quartz is mostly anhedral and displays undulose extinction due to its strained nature (Fig. 4B). The ground mass is mostly fine grained and contains recrystallized fresh quartz grains (Fig. 4C) with significantly increased concentration of fine grained minerals along grain boundaries. The shape of major minerals ranges from euhedral to subhedral. Non-aligned micaceous minerals including biotite and muscovite are common accessories. Minor concentrations of tourmaline, apatite, zircon and ilmenite are also observed.

b. Mansehra granite (MG)

MG is also mega-crystic but a greater degree of alteration of major minerals makes it distinct from UG. Feldspar phenocrysts are mostly dull and cloudy showing their conversion to clay minerals and fine grained epidote grains (Fig. 4D: 4E). The ground mass is medium to coarse grained and exhibit some recrystallization features in the form of fine-grained quartz. Biotite, muscovite, tourmaline, apatite and ore minerals are common accessories. Biotite is mostly well-developed and coarse grained, showing a variable degree of alteration to chlorite and muscovite.

c. Ambela granite (AG)

AG is equigranular and very coarse grained, consisting predominantly of K-feldspar and quartz. Discrete plagioclase is uncommon. K-feldspar is subhedral to euhedral and shows limited alteration in comparison to other minerals. Most grains are perthitic and show well developed albite exsolution (Fig. 4F). Concentration of micaceous minerals is less when compared to UG and MG. Fine grained and fresh recrystallized quartz is very common and occurs along grain boundaries (Fig. 4G).

d. Malakand granite (SG)

SG is petrographically more distinct due to its very fresh and equigranular nature (Fig. 4H: 4I). SG is holocrystalline, coarse grained and contains almost equal amounts of major minerals including quartz, plagioclase and K-feldspar. Feldspars are mostly fresh and display their typical optical properties with very delicate signs of alteration to other minerals. Quartz ranges from subhedral to anhedral and exhibits undulose extinction. Grain boundary recrystallization is lacking in SG when compared to UG, MG and AG. Concentration of micaceous minerals is less when compared to MG and UG. Epidote, allanite, sphene and apatite are other common accessory minerals present.

5. Alteration grade of studied granites

Different schemes recommended for classification of granites based on their degree of weathering and alterations are presented in Table 3. These systems highlight the use of Schmidt hardness, discoloration and disintegration as the classifying criteria in field/hand specimens. The results of various mechanical properties determined during the current investigation are presented in Table 4. Schmidt hardness values of AG, UG and SG (>45) represent values associated with alteration Grade-II, however MG falls within Grade-III, as its hardness is < 45 i.e. 41 (Table 4). No staining related to alteration of minerals is observed in the SG samples; however, AG and UG portray slight discoloration, particularly along grain boundaries (Fig. 2). The degree of yellowish-brown staining on the MG sample is slightly more than other granites, which suggests a higher degree of alteration. Figure 5 shows an image taken from the QEMSCAN analysis that depicts the nature of the void spaces within the studied granitic samples. Quantitative analysis suggests that void spaces constitute more than one percent of area for the MG sample (Table 1). AG also contain considerable void area but it is inconsistent relative to MG (Fig. 5). Voids in MG are more regular and mostly follow intra-granular fractures and cleavages which are more distinct due to the altered and strained nature of mineral grains (mostly feldspar and quartz) (Fig. 5). The relationship of alteration degree with void space and dry density of the studied samples is depicted in Figure 6, which emphasis the higher degree of alteration of MG.

Heidari et al. (2013) described the classification of granitic rocks from western Iran on the basis of degree of weathering using different physical and mechanical properties including porosity, tensile strength, ultrasonic velocities etc. According to these classifications, MG samples exhibit higher alteration grade due to higher voids spaces, lower tensile strength and lower p-wave velocity than other studied granites (Table 4). Olona et al. (2010) related seismic velocities and other geotechnical properties to the grade of weathering of granitic rocks from Spain. They concluded that ultrasonic velocities are significantly reduced with increasing degree of alteration. Comparing their results with values of P-wave velocities (V_p) of granitic rock from the current study shows that UG, AG and SG belong to alteration Grade-II because of having higher V_p values whilst MG has a much lower V_p, which is more typical of Grade-III (Table 4). The results of micro-petrographic index presented in Table 5 suggests and confirms considerably lower I_p values for MG relative to the other granite types. This illustrates that UG, AG and SG granite types belong to similar alteration grade (Grade-II); however, MG portrays a slightly higher degree of alteration and corresponds to alteration Grade-III.

6. Mechanical behaviour of studied granites

The mechanical properties tested include uniaxial compressive strength (UCS), uniaxial tensile strength (UTS) using an indirect Brazillian test, ultrasonic p-wave velocity, Schmidt hardness, elastic modulus and dry density. The corresponding results are presented in Table 4. These results show that MG, assigned Grade III from petrographic and mineralogical analysis, has the lowest strength. Significant changes in the mechanical behaviour of AG, UG and SG is observed despite their similar alteration grade (Table 4). The axial stress against axial and lateral strain response for the granites types tested are presented in Fig 7. This highlights not only differences in UCS but also deformability or stiffness of the studied granites. AG shows higher strength followed by UG and SG respectively. Reduction in elastic moduli with increasing alteration grade is observed (Fig. 8). UCS exhibits positive relationships with UTS, Schmidt hardness and P-wave velocity (Fig. 9). The lower strength of MG resulting from the corresponding higher degree of alteration is consistent with previous work described by Coggan et al. (2013), but variations in mechanical behaviour that occur in samples with analogous alteration (SG, UG and AG) can be attributed to the observed textural changes which are described in more detail below.

7. Discussion

In order to describe the important relationships between petrographic features and mechanical behaviour of the granites studied, textural features including mean grain size and modal concentration of individual major mineral (Quartz, K-feldspar, plagioclase) and mean grain size of rocks have been plotted against corresponding UCS values.

Simple linear regression analysis has been applied to determine the coefficients of determination (r^2) which best describe the relationship between the variables. The values are verified by execution of the t-test method. A critical t-test value of 2.23 was obtained with 10 degrees of freedom and a 95 % confidence limit. The calculated t values for given data were significantly higher than the critical value, confirming the statistical significance of the relationships.

A strong positive relationship exists between the modal concentrations of K-feldspar with UCS but results suggest that increasing amounts of quartz and plagioclase results in decreasing UCS (Fig. 10). This is in direct contrast to work by Sajid and Arif (2014) and Tugrul and Zarif (1999) who suggest a direct correlation with increasing quartz content and UCS. Gunes-Yilmaz et al. (2011) concluded an inverse relation of quartz grain size with UCS but its concentration did not yield any significant relation. In agreement to present observation, Sousa (2013) described inverse relation of quartz content and quartz to feldspar ratio with strength of different Portuguese granites. He also described other textural features of quartz including quartz-quartz contact, quartz-feldspar contacts and quartz deterioration that can negatively influence the strength of granites despite its highest mechanical strength. This may be because of the decrease in rock capacity to accommodate deformation and increase in quartz-quartz contact.

The maximum grain size of quartz, orthoclase and plagioclase display an inverse relationship with UCS (Fig. 11). Similar relationship is also reported by Gunes-Yilmaz et al. (2011) for granites from various other parts of world. Fig. 12 suggests a clear relationship between mean grain size of plagioclase although this relationship is not as obvious with grain size of both quartz and K-feldspar. Strong negative correlations exist when plotting mean grain size of major rock forming minerals (combining quartz, feldspars and micas) and mean size of cleaved minerals (feldspars and micas) against UCS (Fig. 13). The comparison of Fig. 12 and 13 shows that mean grain size of rock is more important in assessing the mechanical behaviour of rock relative to individual grain size of constituent minerals.

Fujii et al. (2007) presented the characteristics of fracture surfaces produced during the tensile strength tests of granite from Japan. According to the authors, pre-existing weak zones and preferred orientation are the most likely areas for fracture dissemination. The appearance and scatter of newly formed fractures and its relation to minerals and mineral boundaries via petrographic observation of post-failure samples (previously subjected to uniaxial loading conditions) are presented in Figure 14. As feldspars in MG are mostly altered, they are more susceptible to propagation of new fracture. An example is presented in Figure (14A) which displays propagation of fractures along the altered zones of an orthoclase mega-cryst. Systematic exsolution can also be targeted for fracturing during compressional loading conditions, as shown in Figure (14B), where K-feldspar develops fractures along the albite exsolution lamellae. Figure (14C) presents a K-feldspar mega-cryst, where newly formed fractures connect various altered zones across the cleavage planes. Similar observations about the fracture propagation and its relation to alteration zones and cleavage planes has been described in Rigopoulos et al. (2013) for diorite and troctolite rock types from ophiolites in Greece. They observed random failure in plagioclase from diorites because of higher degree of alteration while microcraks in fresh plagioclase from troctolite are formed parallel to cleavage planes. It can also be interpreted from this observation that alteration zones can provide more likely areas for fracture initiation relative to pre-existing discontinuities in the form of cleavages in minerals but direction of the applied stress can be a limiting or controlling factor.

Sousa (2014) investigated the petrographic features, modal mineralogy and physico-mechanical properties of different Portuguese granites used as dimension stones. The encouraging and better mechanical behaviour is shown by granites having lower porosity and lesser deformational features for their used as dimension stone. Similar results are obtained for the granites from the present study i.e. samples of MG exhibit significantly higher void spaces and lower strength values (Fig. 5; Table 1 and 4) as compared to other granites (AG, SG and UG) where the voids percentage is considerably lower.

The fracturing behaviour of four different granites types during different cycles of freeze-thaw tests was presented in Freire-Lista et al. (2015). They described the development of different types of fractures during different series of tests. Inter-crystalline fractures were developed during the initial series of testing followed by intra-crystalline fractures in later tests. Quartz and feldspars are the common minerals associated with these fractures. It shows that inter-crystalline fracturing is most likely to occur during compressional conditions; however, grain size seems to be the limitation to this observation as inequigranular rocks are less likely to develop the inter-crystalline fracturing. The presence of fresh cracks along grain boundaries in the failed coarse grained SG sample is clearly demonstrated in Figure 14 (D-E). In contrast, crack propagation in the AG and UG samples is mostly across the minerals grain rather than along grain boundaries (Fig. 14F-14I). This indicates greater resistance shown by grain boundary recrystallization marked by the presence of fresh fine grained quartz grains to compression which ultimately increases the strength of these granites.

As a general observation from thin sections, hand specimen and data presented in Table 2, all studied granites are categorised as coarse grained granites; however, their grain size distribution varies. SG and AG are equigranular, although grain boundary recrystallization in the form of fine grained fresh quartz in AG makes it distinct from SG (Fig. 4). MG and UG are inequigranular with evident mega-crystic nature (Fig. 2 and 4). Equigranular rocks tend to be weaker in comparison to rock with a greater distribution in grain size (Raisanen 2004; Lindqvist et al 2007). The lower strength of SG than UG would support this observation. However, despite the inequigranular nature, the lower UCS of MG than SG would suggest that the higher degree of alteration has a significant influence on the strength characteristics of samples tested.

Fractures tend to propagate more easily in rocks with larger grain boundaries and fine-grained rocks are regarded as stronger than coarse grained rocks. Results from the present study (Table 4) for MG, SG and UG further support this observation. In spite of its coarser grain size, AG is stronger than UG. However, this can be explained using the post-test petrographic observation that intense grain boundary recrystallization in AG has a significant influence on the strength of the granite.

The reliance of mechanical behaviour on textural characteristics has also been described for other rock types apart from granites. Rigopoulos et al. (2010), for example, described the negative effect of the alteration on the mechanical behaviour of dolerites from northern Greece. Secondary minerals e.g. chlorite, formed as a result of alteration can contribute towards higher water absorption and porosity values and hence decrease the strength of dolerites. Diamantis et al. (2014) described the mineralogical control of ultrabasic rocks (peridotites and serpentinites) from central Greece on its mechanical behaviour. The degree of serpentinization has pronounced negative effect on strength and elastic moduli of ultrabasic rocks. Similar observations were made for the Callovo-Oxfordian argillite by Hu et al. (2014) where they observed a negative effect on elastic moduli with increasing clay and water content. Sajid et al. (2009) compared the strength of gabbronorite and amphibolites from northern Pakistan on textural grounds. Amphibolites yielded higher strength than gabbronorites due to a finer grain size and inequigranular nature. All these studies indicate that mineralogical and textural changes due to weathering/ alteration process and increase in the porosity have pronounce negative effect on the mechanical behaviour of rocks irrespective of its composition. Current observations and previous work on granites and other rock types highlight the importance of textural parameters in relation to their mechanical and engineering properties.

8. Conclusions

The relationship between textural features and variation in strength of granites has been investigated for four different granites from northern Pakistan. Three of the studied granites (AG, UG and SG) are associated with alteration Grade-II, while MG is more altered and representative of Grade-III. A series of petrographic, mineralogical and strength tests, together with statistical analyses demonstrate that textural characteristics have a dominant effect on changing the mechanical behaviour of granites. The main conclusions can be summarized as:

1. The mean grain size of feldspars, mean size of main rock forming minerals and mean size of cleaved minerals have a significant negative effect on UCS, UTS, ultrasonic velocity and Schmidt hardness of granites. The results confirm similar interpretations of Gunes-Yilmaz et al. (2011) for granites from various other parts of the world. This study suggests a negative correlation between concentrations of quartz and UCS, which is in direct contrast with the studies conducted on granitic rocks from Turkey (Tugrul and Zarif, 1999). Textural relations of quartz with other minerals would appear more important than concentration alone.

2. From petrographic analysis of failed samples that had previously been subjected to uniaxial loading, fractures generally propagate through connecting grain boundaries in coarse grained rock (e.g. SG). However, recrystallization of minerals along boundaries can have a pronounced positive effect on the strength of granites (e.g. AG).

3. Alteration of granites has a controlling influence on their strength and engineering behaviour. However, textural characteristics have a significant impact on the observed variation in strength for granites with similar alteration grade. Despite the considerable variation in grain size MG yields a low strength due to its higher degree of alteration. The observed variation in strength of UG, SG and AG, with similar alteration grade, can be attributed to differences in their textural characteristics.

4. The petrological features such as exsolution in mineral phases can be potential sources for preferential fracture propagation during compressional loading conditions (Fig. 14B). Altered areas of minerals can also provide preferential locations for fracture initiation/propagation when compared with already present weaker zones in the form of cleavage planes in minerals.

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Table Captions

Table 1. Modal mineralogical concentration of studied rocks

Table 2. Grain size distribution of studied granites

Table 3. Weathering classification systems of granitic rocks

Table 4. Results of various mechanical properties of studied rocks

Table 5. Calculations for micro-petrographic (I_p) index for studied rocks

Table 1. Modal mineralogical concentration of studied rocks

	Qtz %	K-Feldspar%	Pl%	Bt %	Ms%	Tur %	Others %	Voids %
UG-1	35.12	26.23	21.98	5.49	9.65	0.59	0.94	1.0
UG-2	33.39	27.2	22.84	5.73	8.99	1.09	0.76	0.8
UG-3	35.42	25.12	22.69	6.11	9.21	0.95	0.5	0.8
MG-1	38.62	13.26	32.64	6.98	7.09	1.11	0.3	2.5
MG-2	39.12	14.18	31.21	7.89	6.54	1.03	0.03	2.8
SG-1	35.21	28.22	31.02	2.21	3.02	0	0.32	0.9
SG-2	35.11	28.21	30.64	3.12	2.33	0	0.59	0.9
AG-1	25.21	46.93	24.53	3.05	0.08	0	0.2	0.5
AG-2	23.26	47.65	24.64	2.13	0.12	0	2.2	0.5
AG-3	24.09	48.12	23.89	2.65	0.16	0	1.09	0.4

Qtz = quartz, Pl = plagioclase, Bt = biotite, Ms = muscovite, Tur = Tourmaline

Table 2. Grain size distribution of studied granites

	Qtz (mm)		Pl (mm)		K-feldspar (mm)		Bt (mm)	Ms (mm)	Mean grain size (mm)	
	Mean	Max	Mean	Max	Mean	Max	Mean	Mean	Rock forming minerals	cleaved minerals
UG-1	7	14	5.5	29	6	26	0.9	0.8	5.4	5.2
UG-2	7.5	15	4.5	26	6	25	0.9	0.9	5.3	4.3
UG-3	9	17	6	27	7	28	0.9	0.9	6.5	5.1
MG-2	9	18	16	33	4	27	2.4	1.2	9.6	10.0
MG-3	11	19	8	32	8	29	2.2	1.1	8.3	9.4
SG-1	14	19	6	11	5	18	0.4	0.2	8.2	5.1
SG-2	17	19	10	12	5	17	0.4	0.1	9.1	6.9
AG-1	6.5	13	4	5	9	15	0.4	0.1	6.9	6.1
AG-3	8.1	14	3.5	5	7	14	0.4	0.1	6.2	5.6
AG-4	7.2	11	3	6	7	16	0.4	0.1	5.9	4.9

Qtz = quartz, Pl = plagioclase, Bt = biotite, Ms = muscovite

Table 3. Weathering classification systems of granitic rocks

Grade	Rock description	Hencher et al 1990; Anon 1995	Brown, 1981	P-wave velocity (m/sec) Olona et al. 2010
I	Fresh rock	No visible alteration.	No visible sign of rock material Weathering	3320–4315
II	Slightly altered	Slight discoloration and weakening. Schmidt Hammer ‘N’ > 45.	Discolouration indicates weathering of rock materials and discontinuity surfaces	2000-2450
III	Moderately altered	Considerable weakening. Penetrative. Discoloration. Schmidt Hammer ‘N’ 25–45.	Less than half of the rock material is decomposed and/or disintegrated to soil	
IV	Highly altered	Large pieces broken by hand. Schmidt Hammer ‘N’ 0–25.	More than half of the rock material is discomposed and/or disintegrated to soil	518-900
V	Completely altered	Considerably weakened. Geological pick penetrates. Original texture preserved. Slakes readily in water. Hand penetrometer, 50–250 kPa.	All rock material is decomposed and/or disintegrated to soil. The original mass structure is still largely intact	
VI			All rock material is converted to soil. The mass structure and material fabric are destroyed	

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Table 4. Results of various mechanical properties of studied rocks

	Density Dry (kg/m^3)	Dry P-wave Velocity (m/s)	Schmidt Hardness	UCS (MPa)	UTS (MPa)	Modulus (GPa)
UG-1	2615	2601	59	98.6	6.1	25
UG-2	2630	3153	60	139.7	6.3	22
UG-3	2617	2866	58	84.3	5.6	24
MG-1	2561	1570	42	35.0	1.9	5
MG-2	2547	1656	43	35.5	2	6
SG-1	2562	2279	46	105.2	6.7	28
SG-2	2561	2173	48	95.0	6.5	23
AG-1	2573	3227	66	131.0	6.1	38
AG-2	2569	3371	68	137.9	6.5	40
AG-3	2551	3553	69	177.3	6.8	39

Table 5. Calculation of micro-petrographic (I_p) index for studied rocks

	Altered minerals (Am) (%)	Fractures (f) (%)	Sound minerals (Sm) (%)	Ip = Sm/(f+Am)
MG	10.1	0.5	89.4	8.4
MG	9.8	0.9	89.3	8.3
MG	9.2	0.6	90.2	9.2
SG	3.2	0.2	96.6	28.4
SG	2.4	0.1	97.5	39.0
SG	2.7	0.3	97.0	32.3
UG	6.7	0.5	92.8	12.9
UG	5.9	0.4	93.7	14.9
UG	5.7	0.3	94.0	15.7
AG	3.3	0.1	96.6	28.4
AG	3.9	0.1	96.0	24.0
AG	2.7	0.4	96.9	31.2

Figure Captions

Figure 1. Geological map of north-west Pakistan showing location of studied granites

Figure 2. Representative cylindrical core samples of studied granites

Figure 3. Representative mineral maps of studied granites generated via QEMSCAN analysis

Figure 4. Micrographs illustrating A) alteration of Plagioclase feldspar, B) quartz showing undulose extinction, C) fresh recrystallized quartz grain in ground mass, D-E) plagioclase alteration to clay minerals and epidote, F) perthitic alkali feldspar, G) grain boundary recrystallization of quartz, H-I) fresh and equigranular quartz and feldspar grains

Figure 5. Distribution of voids spaces (represented by red colour) in studied granites. Image generated via QEMSCAN analysis

Figure 6. Plot representing decrease in dry density with increasing void spaces.

Figure 7. Response of axial stress versus axial and lateral strain of studied granites

Figure 8. Relationship between elastic modulus and uniaxial compressive strength for samples with different alteration grade. Symbols are same as in Figure 6.

Figure 9. Plots showing positive relationship of UCS with UTS, Schmidt hardness and ultrasonic velocities. Symbols are same as in Figure 6.

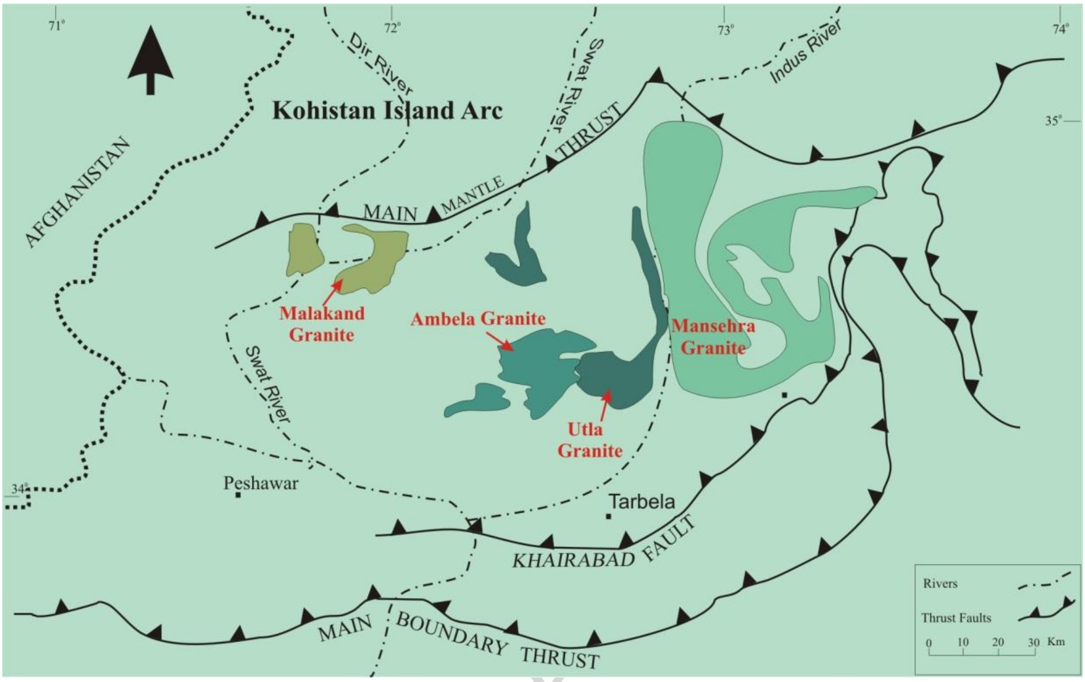
Figure 10. Relationship of modal abundance of quartz, K-feldspar and plagioclase with UCS. Symbols are same as in Figure 6.

Figure 11. Relationship of maximum grain size of quartz, K-feldspar and plagioclase with UCS. Symbols are same as in Figure 6.

Figure 12. Relationship of mean grain size of quartz, K-feldspar and plagioclase with UCS. Symbols are same as in Figure 6.

Figure 13. UCS against mean grain size of rock and mean grain size of cleaved minerals. Symbols are same as in Figure 6.

Figure 14. Post-test micrographs illustrating A) fracture propagation along the altered zones of K-feldspar, B) fracture development along exsolution lamellae, C) fracturing of mineral across the cleavages connecting the altered zones, D-E) fracture spread along the grain boundaries, F-I) fracturing of minerals across the mineral grain. Arrows point towards the direction of compressional stress during strength tests



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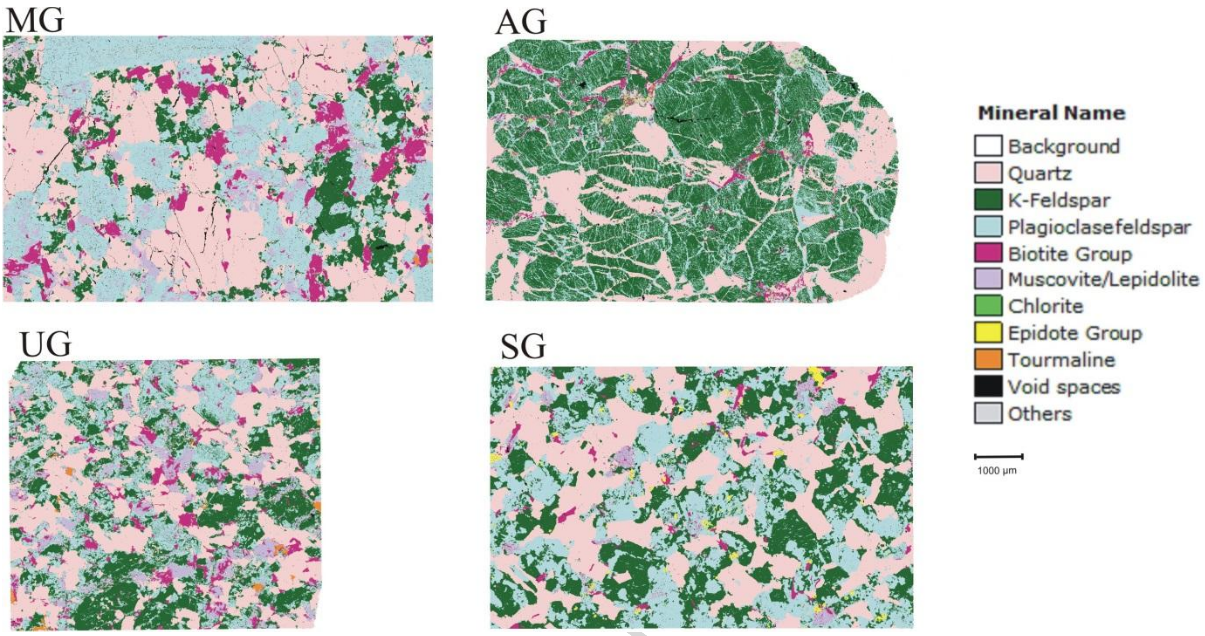

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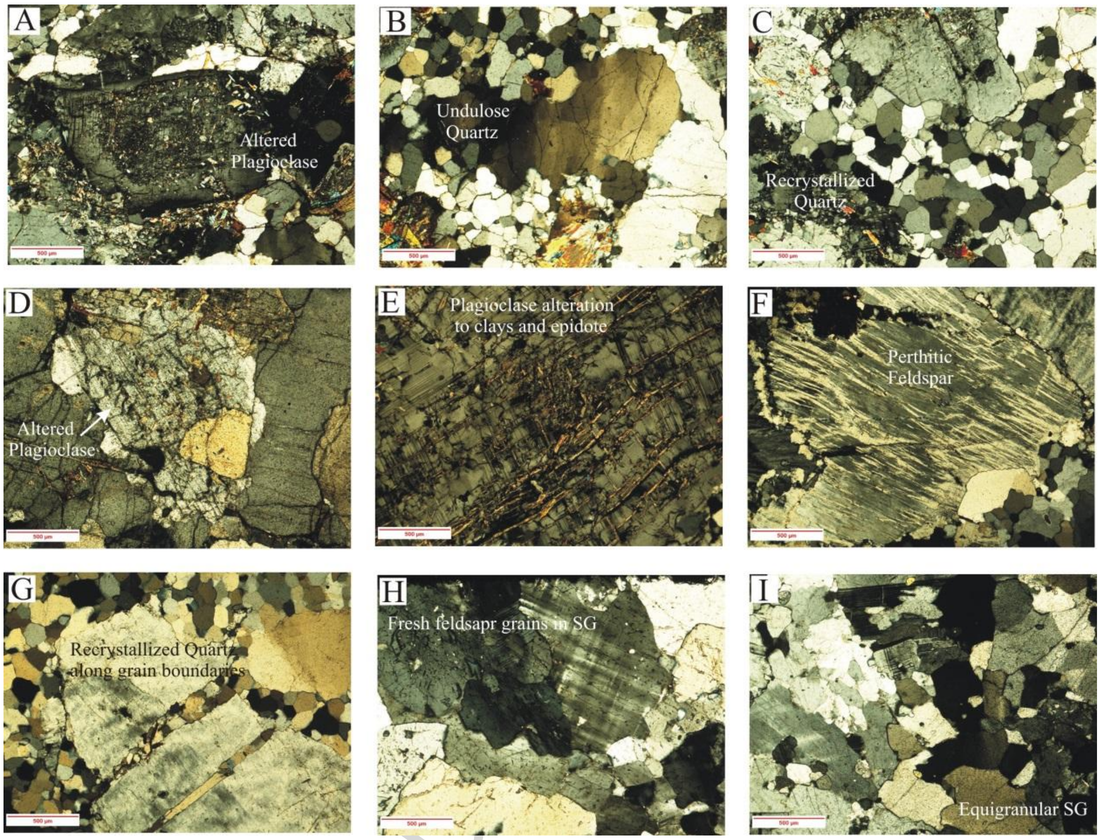

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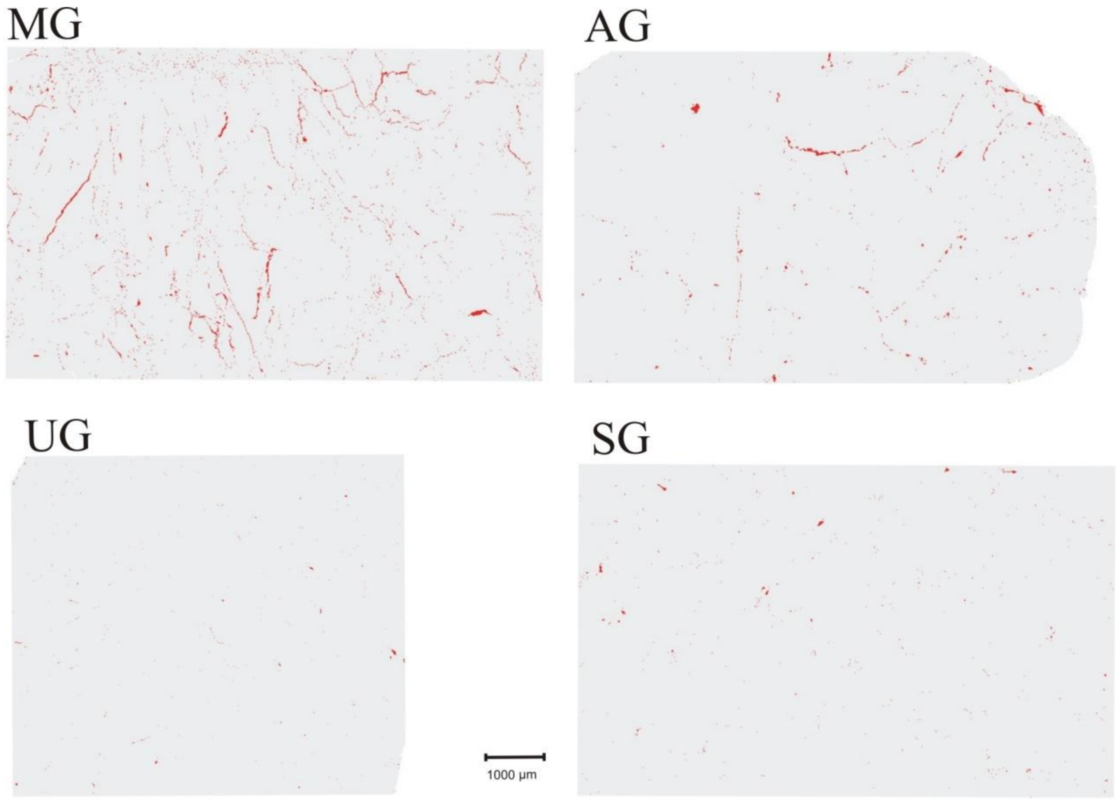

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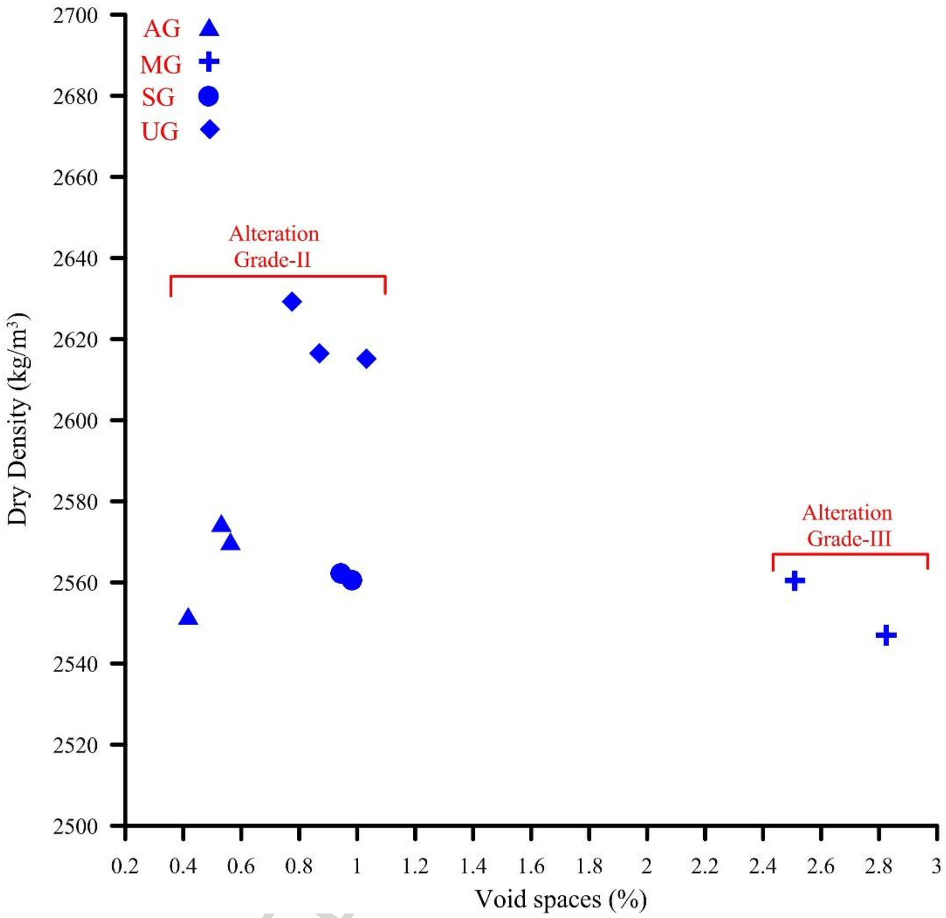

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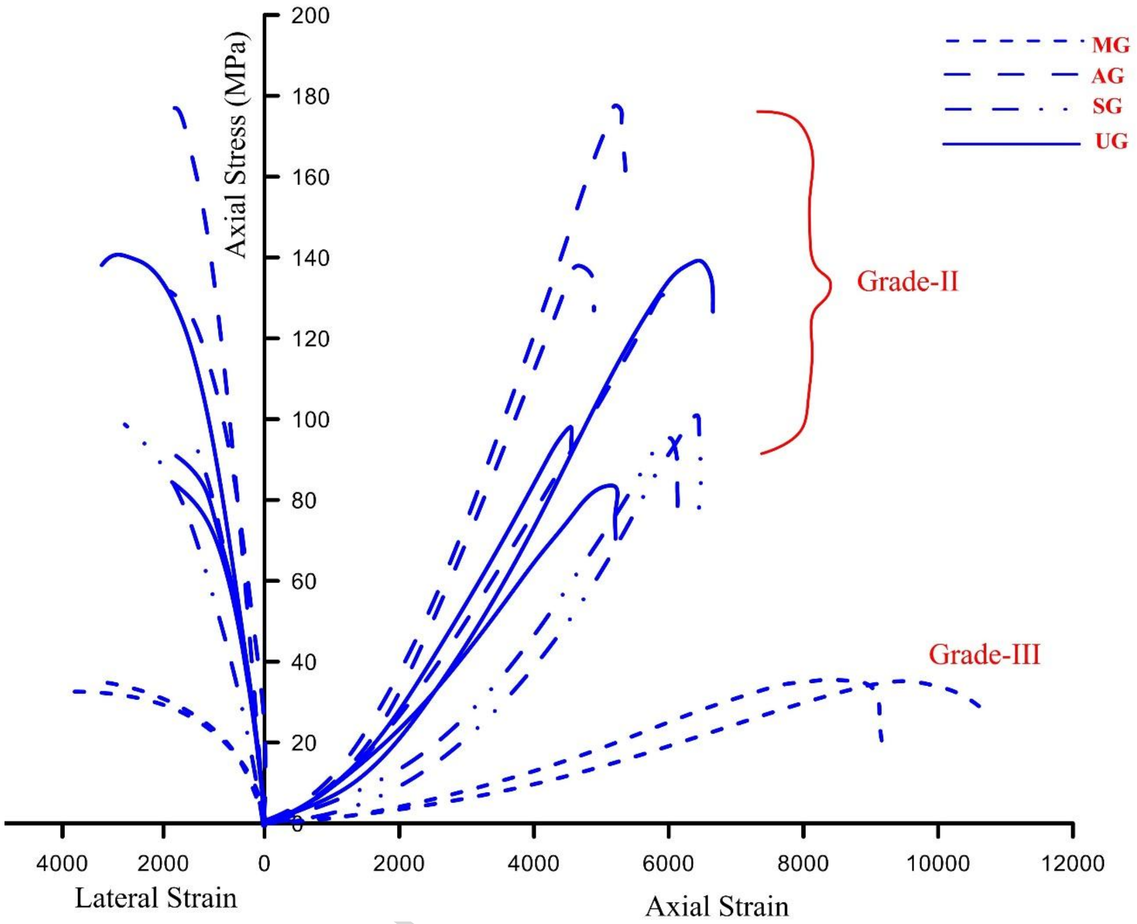

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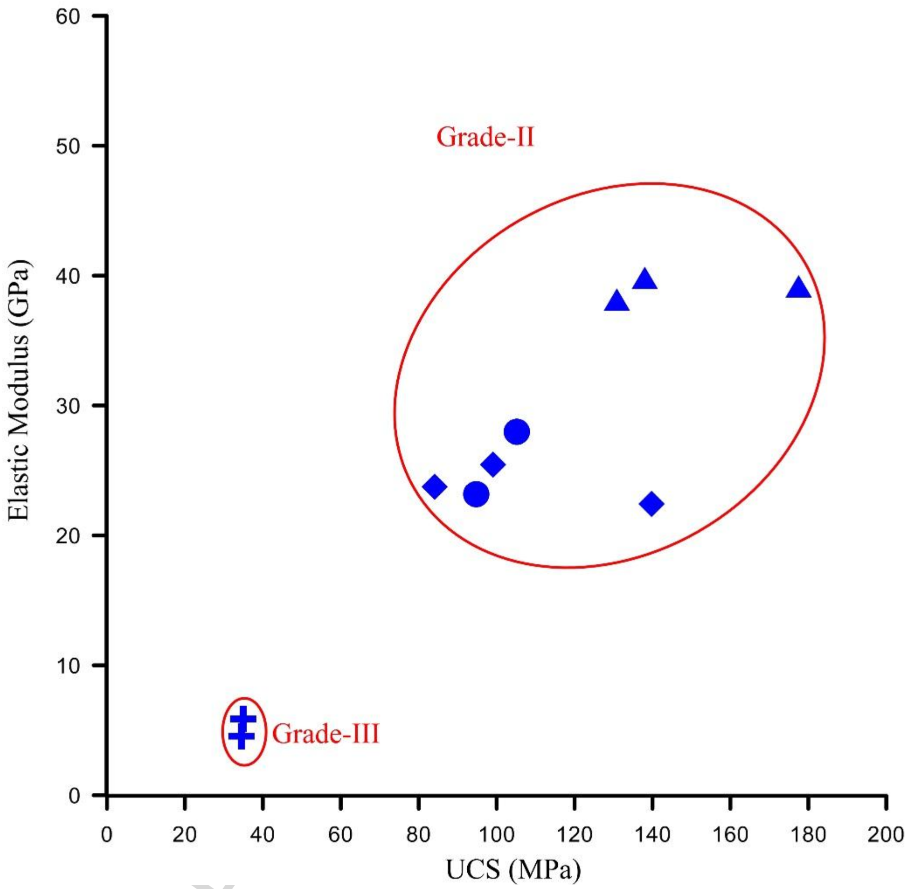

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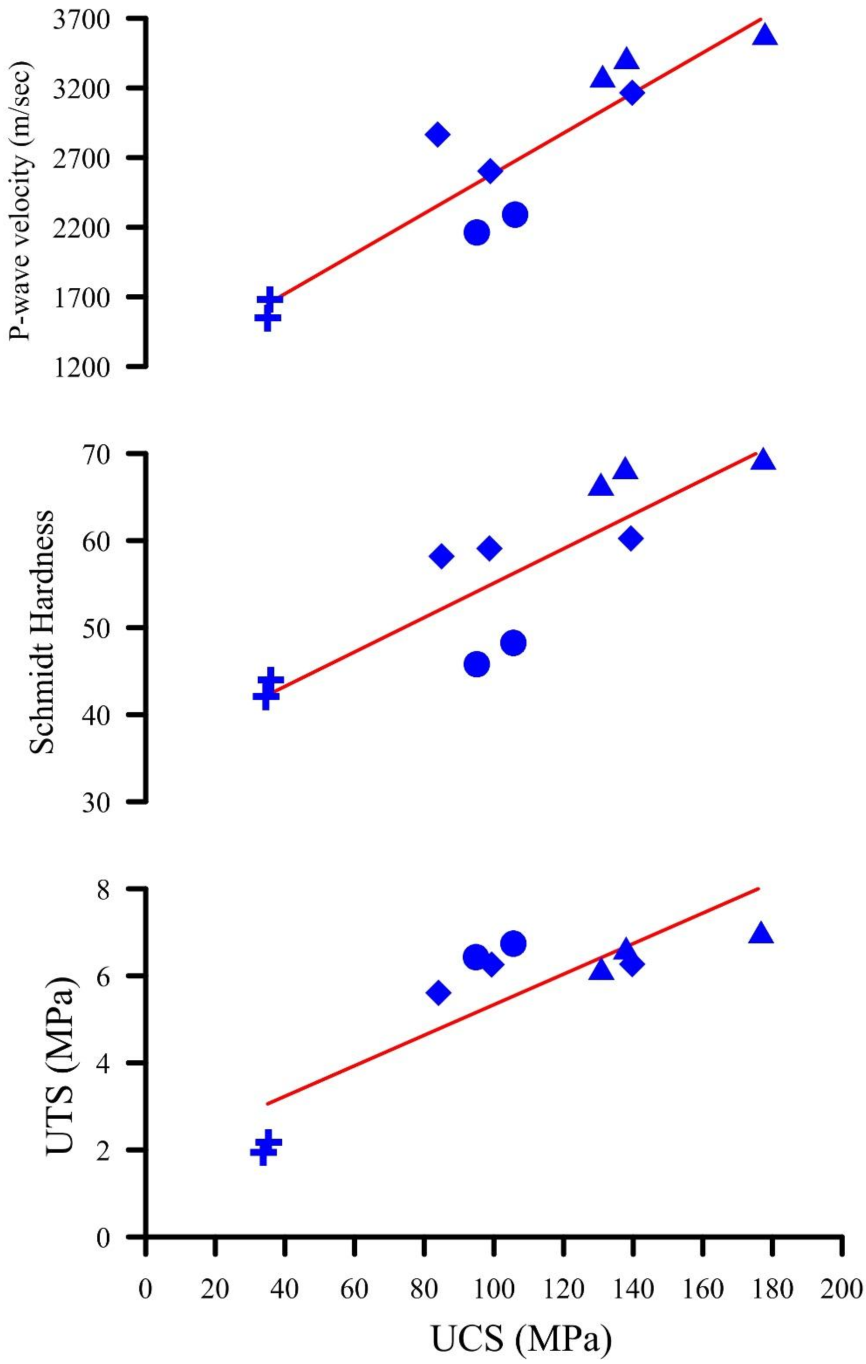

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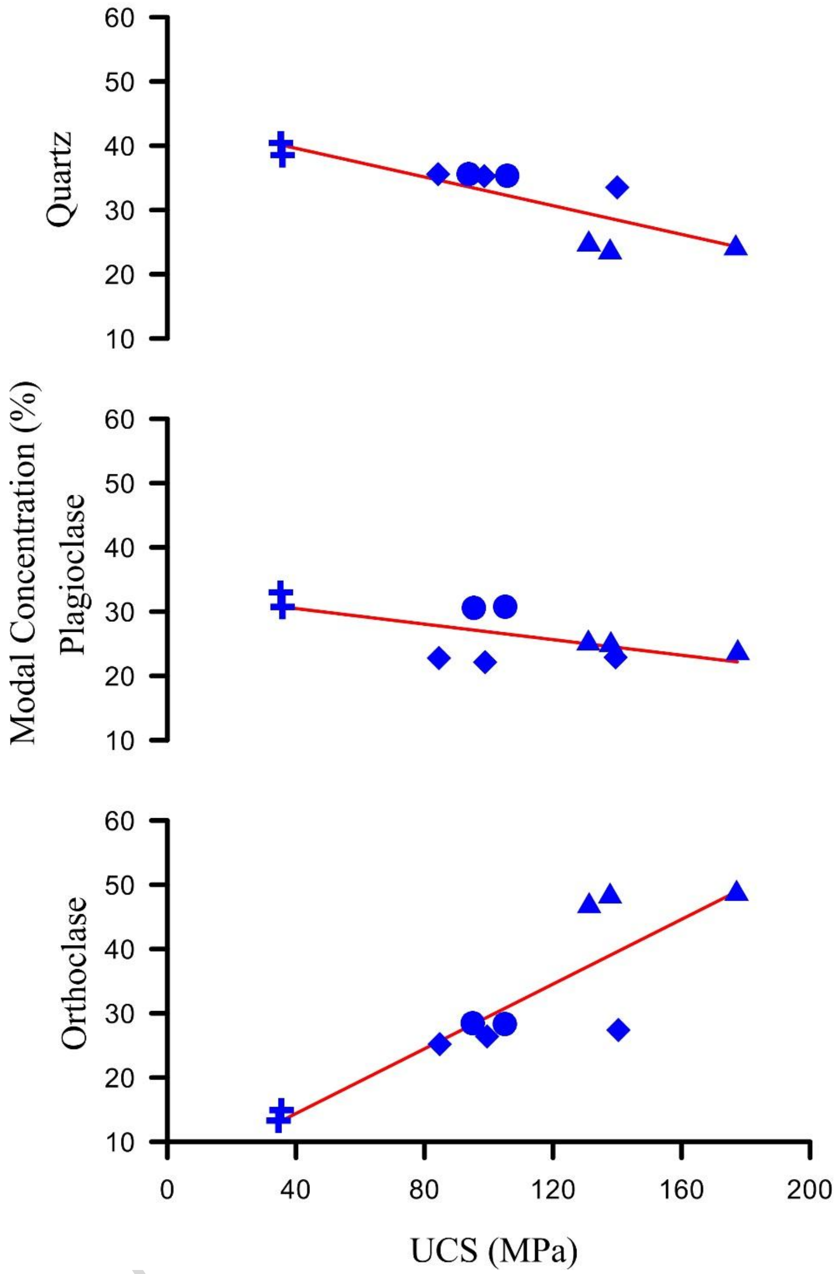

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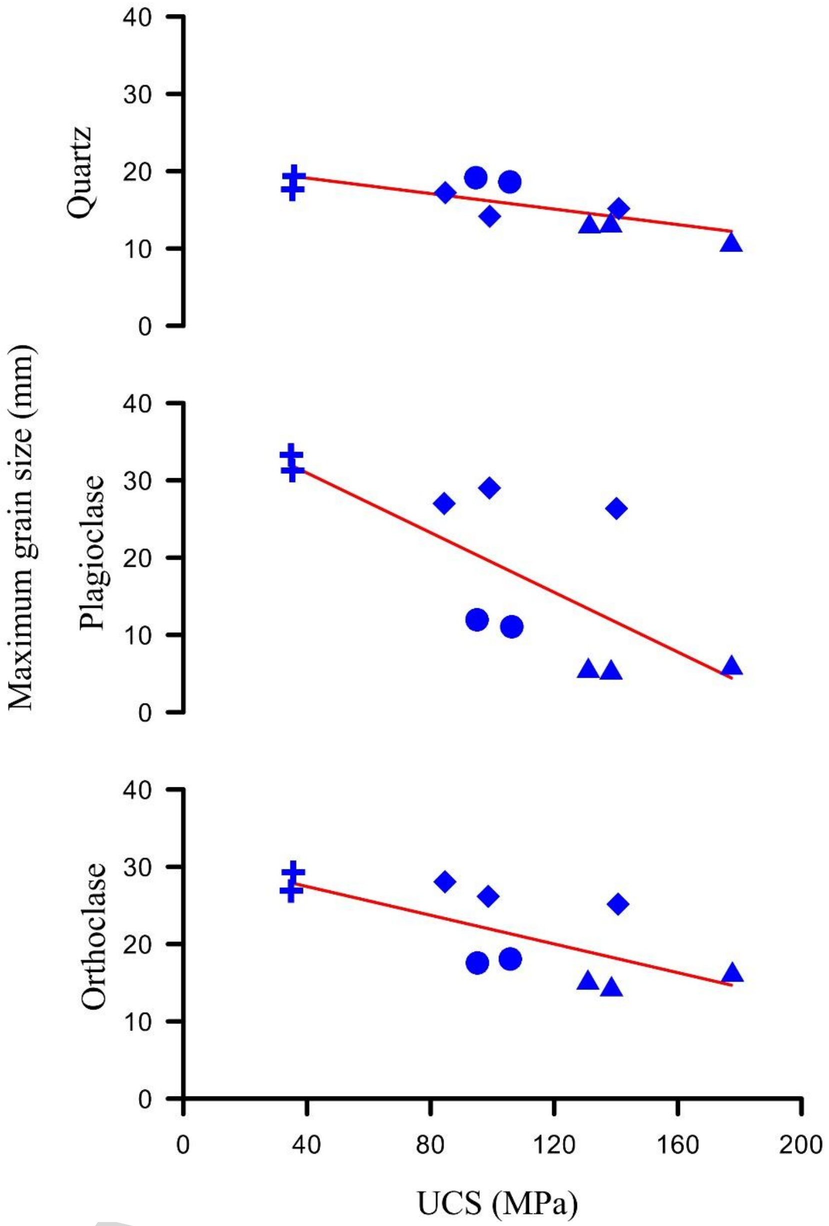

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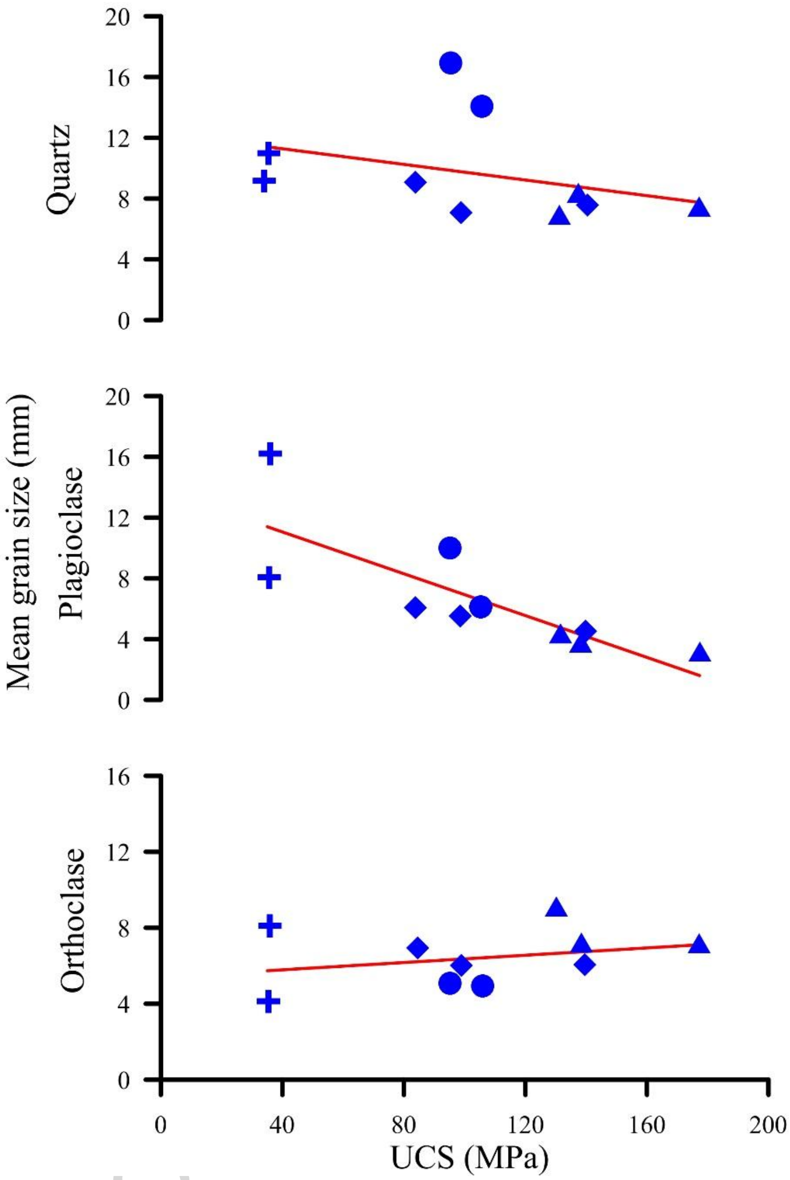

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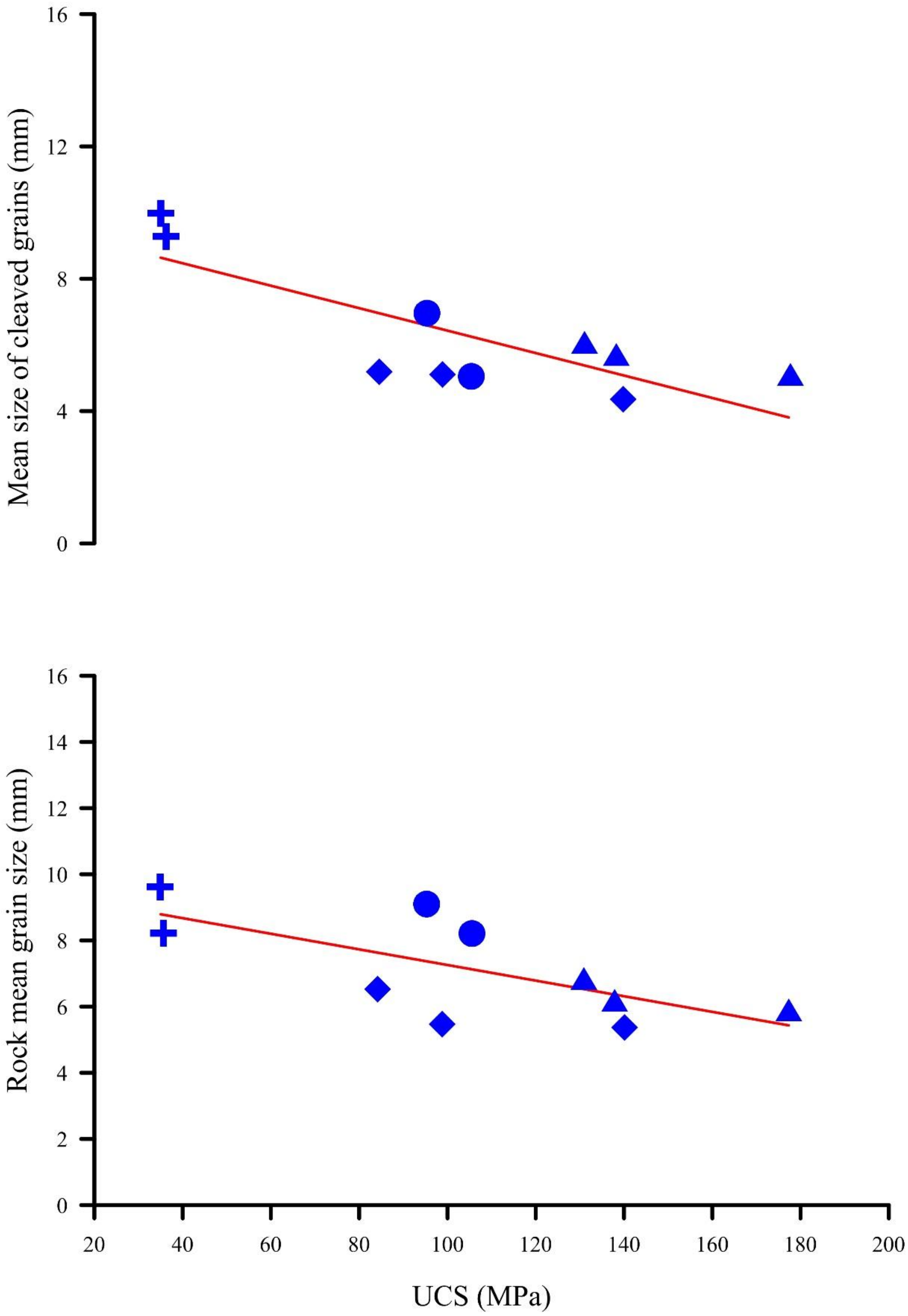

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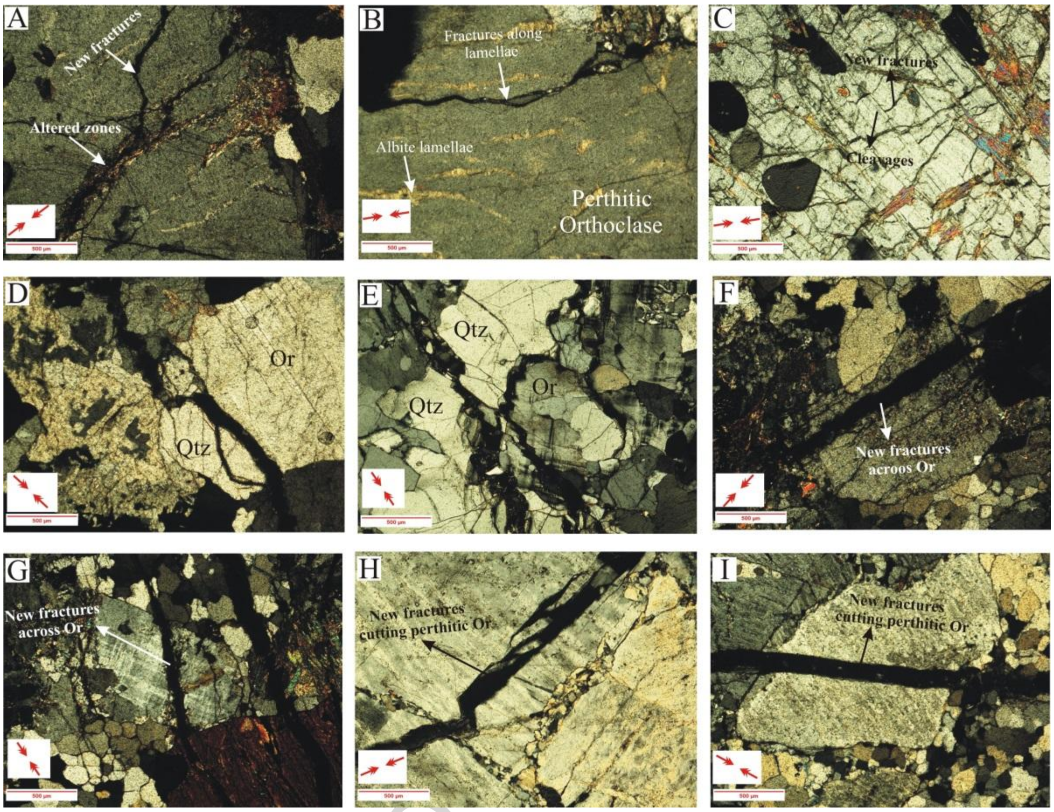

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HIGHLIGHTS

- Textural characteristics of four different granites are examined
- Three of granites types have alteration Grade-II while other has Grade-III
- Strength, hardness, density, voids and ultrasonic velocity have been determined
- Statistical analyses and post-test petrography relate textures with rock strength
- Textural features have major influence on granite strength with similar alteration